*The intriguing life of massive galaxies*
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# The size and mass evolution of the massive galaxies over cosmic time

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**Abstract.**
Once understood as the paradigm of passively evolving objects, the discovery that massive galaxies experienced an enormous structural evolution in the last ten billion years has opened an active line of research. The most significant pending question in this field is the following: which mechanism has made galaxies to grow largely in size without altering their stellar populations properties dramatically? The most viable explanation is that massive galaxies have undergone a significant number of minor mergers which have deposited most of their material in the outer regions of the massive galaxies. This scenario, although appealing, is still far from be observationally proved since the number of satellite galaxies surrounding the massive objects appears insufficient at all redshifts. The presence also of a population of nearby massive compact galaxies with mixture stellar properties is another piece of the puzzle that still does not nicely fit within a comprehensive scheme. I will review these and other intriguing properties of the massive galaxies in this contribution.

**Keywords.** galaxies: elliptical and lenticular, cD, galaxies: evolution, galaxies: formation, galaxies: fundamental parameters, galaxies: high-redshift, galaxies: structure

## 1. Introduction

The discovery that massive galaxies were much more compact in the past (Daddi et al. 2005; Trujillo et al. 2006) revolutionized our traditional picture of how these objects have developed with cosmic time. A monolithic-like scenario, where the bulk of the stellar population as well as the structure of these galaxies are form in a single dissipative event followed by a passive evolution, is not longer supported by the observations.

As any shift in scientific paradigm, there has been an enormous debate about the reality of this huge structural evolution. Most of the critics against this discovery focused on the reliability of the size estimations and the accuracy of the stellar mass determinations of these $z>1$ objects (e.g. Mancini et al. 2010; Muzzin et al. 2009). Today, ultra-deep observations of these galaxies (e.g. Carrasco et al. 2010; Cassata et al. 2010) as well as the first dynamical estimations of their masses (e.g. Cenarro & Trujillo 2009; Cappellari et al. 2009) have inclined the vast majority of the community to accept as real the size evolution of the massive galaxies. But not only the size of the massive galaxies have dramatically changed with comic time, also the morphological content among the family of massive galaxies has drastically varied as redshift decreases (see Fig. 1). In fact, present-day massive galaxies are composed mostly by objects with spheroidal-like appearance. At high-z, the most common morphology of the massive galaxies resembled disk-like structures (e.g. van der Wel et al. 2011; Buitrago et al. 2011).

The stellar mass-size relation of massive galaxies seem to be at place (although with a different "zeropoint" position than in the present-day universe) since at least $z\sim3$

(e.g. Trujillo et al. 2007; Buitrago et al. 2008) and the scatter along this relation has not significantly changed since then (see Fig. 2). However, the number of galaxies that populate these relations have grown with time as the number density of massive galaxies have continuously increasing since that epoch (e.g. Pérez-González et al. 2008). That means that the new massive galaxies that are incorporated in the stellar mass-size relation are located in such sense that do not alter dramatically this relation. In order to maintain the scatter of this relation relatively constant with time, the newcomers should evolve later in size similarly as the older galaxies that already populated the stellar mass-size relation.

On what follows I will summarize the different scenarios that have been proposed to explain the significant structural change of the massive galaxies as well as the observational evidence favoring the different mechanisms. We adopt a cosmology with $\Omega_m$=0.3, $\Omega_\Lambda$=0.7 and $H_0$=70 km s$^{-1}$ Mpc$^{-1}$.

## 2. What is the physical mechanism behind the size evolution?

If we accept the reality of the structural evolution of the massive galaxies, the next question to solve is how these objects have reached their present configuration. We can summarize the different proposed scenarios in three categories. It is worth stressing that the following mechanisms can take all place simultaneously and certainly they should all have a role in the evolution of the massive galaxies. Consequently, when we use the word rejected or supported by the observations we will be referring to the role of such mechanism as the main driver of the size evolution.

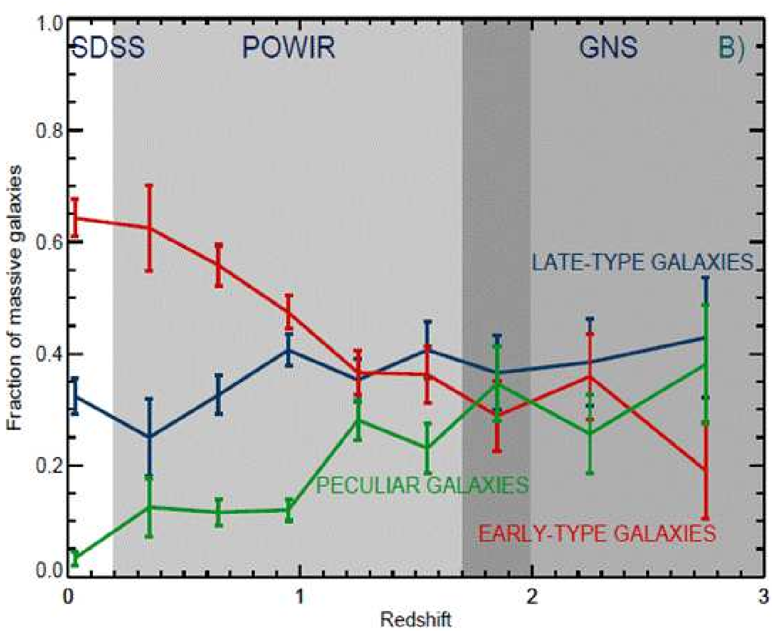


**Figure 1.** Fraction of massive ($M_\star \sim 10^{11} M_{sun}$) galaxies as function of redshift segregating the objects according to their visual morphological classification. Blue color represents late type (S) objects and red early type (E+S0) galaxies, while peculiar (ongoing mergers and irregulars) galaxies are tagged in green. Different color backgrounds indicate the redshift range expanded for each survey used: SDSS, POWIR/DEEP2 and GNS. Error bars are estimated following a binomial distribution. Figure taken from Buitrago et al. (2011).

• Major mergers. This was the earliest theoretical suggestion (e.g. Naab et al. 2007; Nipoti et al. 2010) and it was also the first hypothesis rejected by the observations (e.g. Bundy et al. 2009; Wild et al. 2009; de Ravel et al. 2009; Bluck et al. 2009; López-San Juan et al. 2010). Simply, there is not enough number of major mergers that can account by the huge size evolution observed (a factor of 4 since z∼2; Trujillo et al. 2007) plus the relatively modest evolution in stellar mass (a factor of 2 since z∼2; van Dokkum et al. 2010). The predicted size evolution as a function of the increase in mass goes as: $\Delta r_e \propto \Delta M$ in major mergers (e.g. Ciotti & van Albada 2001; Boylan-Kolchin et al. 2006) which is insufficient to produce the observed size evolution.

• Puffing up. Fan et al. (2008; 2010) as well as Damjanov et al. (2009) proposed a scenario where the size evolution is connected to the massive expulsion of gas by the effect of an AGN (Fan et al.) or stellar winds (Damjanov et al.). According to this mechanism, the removal of gas changes the gravitational potential of the galaxy making the object to puff up to its new (larger) configuration. This evolution is fast ($\lesssim$1 Gyr; Ragone-Figueroa & Granato 2011) and the model predicts a dichotomy of massive objects at all redshifts: young ones (<1 Gyr) with small sizes and high velocity dispersions (∼400 km/s) and old ones (>1 Gyr) with present-day sizes and moderate velocity dispersion (∼200 km/s). This is not observed in nature: massive compact galaxies at high-z are "old" at those epochs and there is not an age segregation in the stellar mass-size relation since, at least,

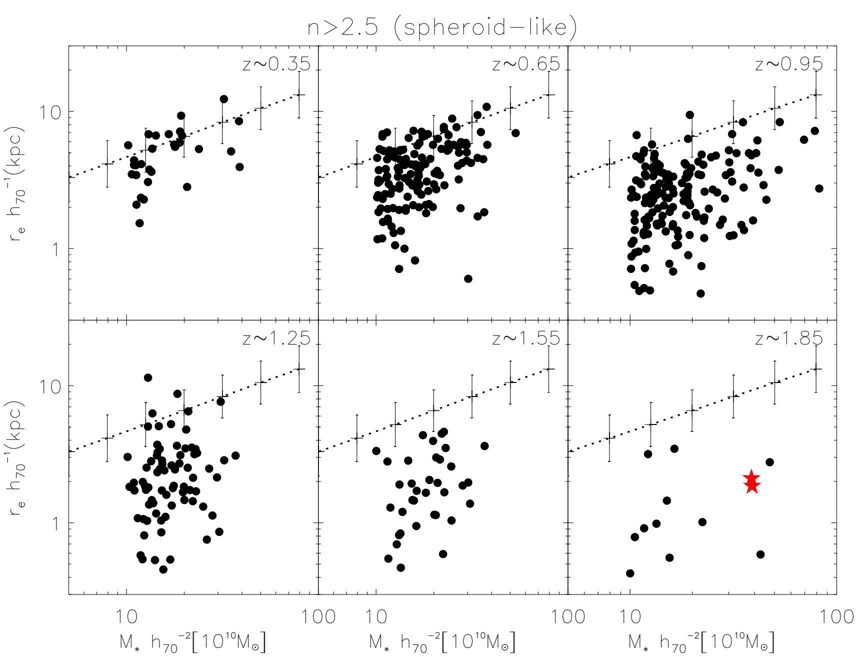


**Figure 2.** Stellar mass-size distribution of our high-concentrated (spheroid-like) galaxies. Over–plotted on the observed distribution of points are the mean and dispersion of the distribution of the Sérsic half-light radius of the SDSS early-type (n>2.5; Shen et al. 2003) galaxies as a function of the stellar mass. For clarity, individual error bars are not shown. The mean size relative error is <30 per cent. Uncertainties in the stellar mass are ∼0.2 dex. Solid black points are from the ACS sample of Trujillo et al. (2007), red stars from Carrasco et al. (2010) Gemini high resolution imaging.

z=1 for objects with spheroid-like morphologies (Trujillo et al. 2011). Summarizing, this scenario is also not favored observationally.

• Minor mergers. This model (Khochfar & Burkert 2006; Maller et al. 2006; Hopkins et al. 2009b; Naab et al. 2009; Sommer-Larsen & Toft 2010; Oser et al. 2010) proposes that most of the size evolution of the massive galaxies has taken place due to the continuous accretion of minor bodies. The stars of these merged satellites are mainly located in the periphery of the main body, making this mechanism an excellent vehicle for the size evolution. The predicted increase in size as a function of the increase in mass goes as: $\Delta r_e \propto \Delta M^2$ (e.g. Naab et al. 2009). This evolutionary path predicts the following observables: a continuous increase in size of the global population of massive galaxies, a size growth not related with the age of the main galaxy, a mild velocity dispersion evolution of the massive galaxy with time (Hopkins et al. 2009b).

## 3. Observational evidence favoring the minor merging scenario

There are many observational evidences favoring the minor merging hypothesis as the main channel of massive galaxies growth. We can summarize them in three groups:

• The size evolution of the spheroid-like massive galaxies is not related with the age of their stellar population. Since z∼1, spheroid-like massive galaxies, at a given fixed stellar mass, still need to grow by a factor ∼2 to reach their present configuration. This significant size evolution is observed, at all redshifts, to be independent of the stellar age of the massive galaxies (Trujillo et al. 2011). This observation points out to a size growth mechanism that does not know about the age of the main galaxy. An external accretion of stars (where the infalling satellites do not have previous knowledge about the age of the central galaxy) fits well within this scheme.

• There is a progressive and steady formation of the outer galaxy envelopes. The central stellar mass density of the massive galaxies at high-z do not dramatically differ from the central stellar mass density of the nearby massive galaxies (Bezanson et al. 2009; Hopkins et al. 2009a). The majority of the evolution of the stellar mass density profile of the massive galaxies has taken place at their extended wings. Massive galaxies have steadily increased their number of stars at farther distances (van Dokkum et al. 2010). This progressive build is very suggestive of a continuous accretion of new stars with cosmic time in the periphery of these galaxies.

• At a fixed stellar mass, the velocity dispersion of the massive galaxies has mildly declined since z∼2. Cenarro & Trujillo (2009) compiled from the literature the velocity dispersions of many massive ($M_\star \sim 10^{11} M_{sun}$) galaxies since z∼2. This compilation took data from van der Wel et al (2005; 2008) at 0.5<z<1 and di Seregho Allighieri et al. (2005) at z∼1. This data was complemented with the measurement of the velocity dispersions of massive galaxies in the SDSS (for having a local reference) and with the first estimation of the velocity dispersion of massive galaxies at z>1.5 (using the published staked spectrum of Cimatti et al. 2008). All this data together (see Fig. 3) clearly indicated that the evolution of the velocity dispersion of the massive galaxies, at a fixed stellar mass, has only moderately declined with cosmic time. This result has been later confirmed by many new estimations of the velocity dispersion of massive galaxies at 1.5<z<2 (e.g. Cappellari et al. 2009; Onodera et al. 2010; van de Sande et al 2011; Newman et al. 2010, Toft et al. 2012). This mild evolution of the velocity dispersion is in good agreement with the idea that most of the structural evolution of the massive galaxies has taken place in their outer regions. This again fits well with a scenario of accretion of new stars that is smooth and mostly locate stars in the periphery of these objects. The fact that the central stellar mass density of the massive galaxies has only changed mildly since z∼2

also agrees with the fact that the central velocity dispersion of these objects have not changed significantly (see a much elaborated discussion of this point in Trujillo et al. 2012).

## 4. Some puzzling observations

So far, both the cosmological simulations as well as the observational evidence favor the minor merging scenario as the main driver of size and mass evolution of the massive galaxies. However, there are two observational evidences that are not easy to understand, at least with the present theoretical development, within the minor merging hypothesis. These two puzzling observations are: the scarcity of massive compact galaxies in the local universe and the factor of 2 less satellites surrounding the massive galaxies at all redshifts compared with the model predictions.

### 4.1. *Nearby massive compact galaxies: relics of the early universe?*

After the discovery that massive galaxies at high-z were compact, there was an observational effort to try finding massive ($M_\star \sim 10^{11} M_{sun}$) and compact ($r_e \sim 1$ kpc) objects

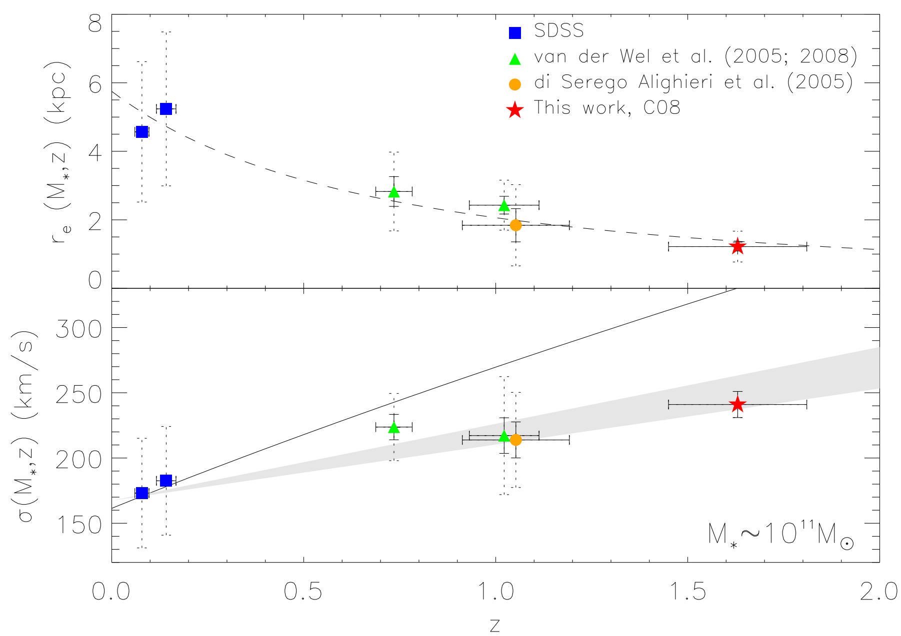


**Figure 3.** Top panel: size evolution of $M_\star \sim 10^{11} M_{sun}$ spheroid-like galaxies as a function of redshift. Different symbols show the median values of the effective radii for the different galaxy sets considered in this work (see Section 3), as indicated in the labels. Dashed error bars, if available, show the dispersion of the sample, whereas the solid error bars indicate the uncertainty of the median value. The dashed line represents the observed evolution of sizes $r_e(z) \propto (1+z)^{-1.48}$ found in Buitrago et al. (2008; B08) for galaxies of similar stellar mass. Bottom panel: velocity dispersion evolution of the spheroid-like galaxies as a function of redshift, with symbols as given above. Assuming the B08 size evolution, the solid line represents the prediction from the "puffing-up" scenario (Fan et al. 2008), whereas the gray area illustrates the velocity dispersion evolution within the merger scenario of Hopkins et al. (2009b) for $1<\gamma<2$. Figure from Cenarro & Trujillo (2009).

in the nearby Universe (see Fig. 4). According to the theoretical predictions (Hopkins et al. 2009b) around 10% of the massive compact galaxies since z∼2 should have survived intact due to the stochastic nature of the merging channel. Taking into account that the number density of massive galaxies at z∼2 was a factor of 10 smaller than today, around 1% of the present-day massive galaxy population should be composed by relics (i.e. they should appear today as old compact massive galaxies) from that early epoch of the Universe. Observationally, it is found that less than 0.03% of the current massive galaxies are as compact as the ones found at z∼2 (Trujillo et al. 2009). Moreover, these galaxies are not only very scarce (see also Taylor et al. 2010) but young (∼2 Gyr; Ferré-Mateu et al. 2012). Consequently, it seems that massive compact relics of the early universe are non-existent today.

Valentinuzzi et al. (2010) have argued against the above findings and claim that old and dense massive galaxies can be found in large numbers in galaxy clusters environments. This will alleviate the problem for minor merging scenarios. However, it is difficult to understand why these nearby massive compact objects have not popped out in the SDSS survey (which contain many of these galaxy clusters). So, the controversy still remains open and further investigation is required.

### 4.2. *Satellites surrounding massive galaxies: are they enough?*

If the minor merging scenario is the main channel of massive galaxy evolution one would expect that a direct test of this hypothesis could be done by counting the number of satellites surrounding these galaxies and exploring their evolution with redshift. Estimating the number of satellites around massive galaxies have been done by many authors (Kavi-

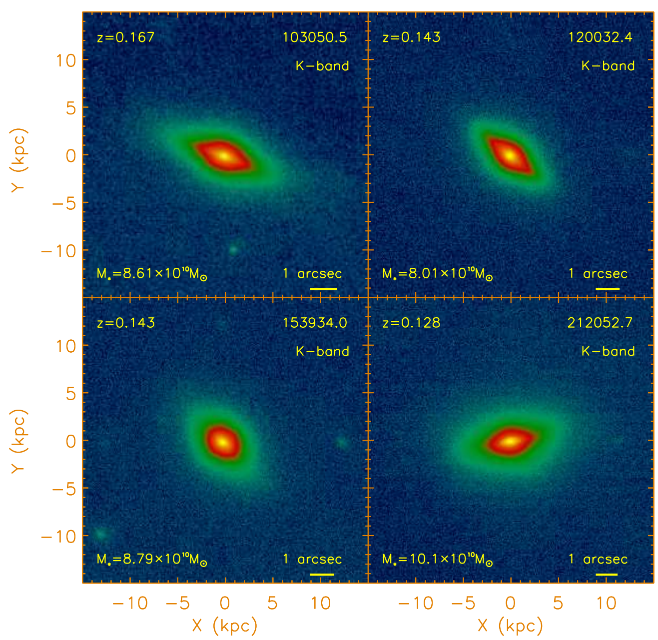


**Figure 4.** K-band Gemini high-resolution (FWHM∼0.2 arcsec) imaging of four nearby (z∼0.15) massive compact galaxies. Listed on each figure is the galaxy name, its stellar mass, and its spectroscopic redshift. The solid line indicates 1 arcsec angular size. Figure taken from Trujillo et al. (2012).

raj et al. 2009; Jackson et al. 2010; Nierenberg et al. 2011; Man et al. 2012; Newman et al. 2012; Mármol-Queraltó et al.2012a). As expected, the fraction of massive galaxies with nearby satellites depends on two parameters: the search radius to find the satellite and the mass ratio between the massive galaxy and the satellite. To give a number, Liu et al. (2011) found that around 13% of the local galaxies with $M_{\star} \gtrsim 10^{11} M_{sun}$ have a satellite with a mass ratio 1:10 or smaller within a projected radius of 100 kpc to the host galaxy. This fraction is constant with redshift (Mármol-Queraltó et al. 2012a; at least up to z$\sim$2). If the explored mass ratio is decreased down to 1:100, the fraction of massive galaxies with a nearby satellite increases up to $\sim$30%.

The above fractions can be directly compared with the predictions from ΛCDM cosmological simulations. In particular, these numbers can be confronted with the semianalytical predictions based on those simulations. This simply exercise was conducted by Quilis & Trujillo (2012) using three different semianalytical models (Bower et al. 2006; De Lucia & Blaizot 2007 and Guo et al. 2011) run over the Millenium I (Springel et al. 2005) and Millenium II (Boylan-Kolchin et al. 2009) simulations. Interestingly, the theoretical models predicted correctly the constancy on the fraction of massive galaxies with nearby satellites across the cosmic time. However, all models overpredicted by a factor of $\sim$2 the value of this fraction (see Fig. 5). In other words, in the simulations there is an excess of satellites that could later merge with the massive host galaxy. Whether this excess of satellites in the simulations is also overpredicting the size evolution that is obtained in the simulations is a matter of analysis at the moment of writing this review.

## 5. Open questions

There are a number of observational predictions associated to the minor merging scenario that could be tested with new observations. One of these predictions is a significant radial change in the stellar population properties of the massive galaxies. In particular, one would expect an age and metallicity gradient if the infalling satellites have progressively form the outer parts of the massive galaxies. In this scheme, the outer regions of the massive galaxies should be progressively young and metal poor.

Age gradients should be extremely difficult to measure observationally in present-day massive galaxies. Our ability to distinguish among a few Gyr different old stellar populations is very limited at present. The stars accreted through the infalling satellites should be relatively evolved at the moment of the merger and, after the infall to the main galaxy, no new star formation is expected to occur. Consequently, we should not expect many evidence of minor merging happened at z$\gtrsim$0.5 exploring age gradients of nearby massive galaxies. However, metallicity gradients should be more easily identified in present-day massive galaxies as the metallicities of the stellar populations should not evolve with cosmic time.

There are a few but increasing number of studies exploring age and metallicity radial gradients in nearby massive galaxies up to several effective radii (Coccato et al. 2010; Tal et al. 2011; Greene et al. 2012; La Barbera et al. 2012). These studies agree on a metallicity decrease of the stellar populations of massive galaxies towards the outer regions. These works, however, are still at their infancy as measuring the stellar population properties at such distances is complicated due to the low surface brightness of the stellar populations at those radii.

Another further advance that is expected in the next few years is the measurement of the stellar population properties of the satellite galaxies that will eventually merge with the massive galaxies. This information is key if we want to close the loop with the evidence compiled from the outer parts of present-day massive galaxies. A strong consistency test

for the minor merging scenario is that the information provided by both types of works agrees. A few studies have pioneered the analysis of the stellar populations of satellite galaxies at high-z (Newman et al. 2012; Mármol-Queraltó et al. 2012b). High-z satellites had similar ages than their massive hosts but that changed with time, and present-day satellites are much younger than their massive galaxy. Measuring metallicities of the satellite galaxies at high-z has not been conducted yet. A step further in this sense it is expected with the new SHARDS survey (Pérez-González et al. 2012) conducted with the 10.4 m GTC telescope at La Palma.

## 6. Summary

The discovery that massive galaxies were much more compact in the past has opened a fruitful era of research trying to put this finding within a galaxy formation context. Both theory and observations seem to converge to a scenario where the main channel of size and mass evolution of the massive galaxies is through a continuous accretion of minor bodies as cosmic time progresses. This active life of the massive galaxies follows after a rapid (dissipative) collapse which would have form the bulk of the present-day body of the most massive objects (see e.g. Dekel et al. 2009; Ricciardelli et al. 2010; Wuyts et al. 2010; Bournaud et al. 2011; Targett et al. 2011; Barro et al. 2012).

Although the general picture of massive galaxy evolution seems to be at place, still a few observational results challenge this scenario: the nearly absence of old compact

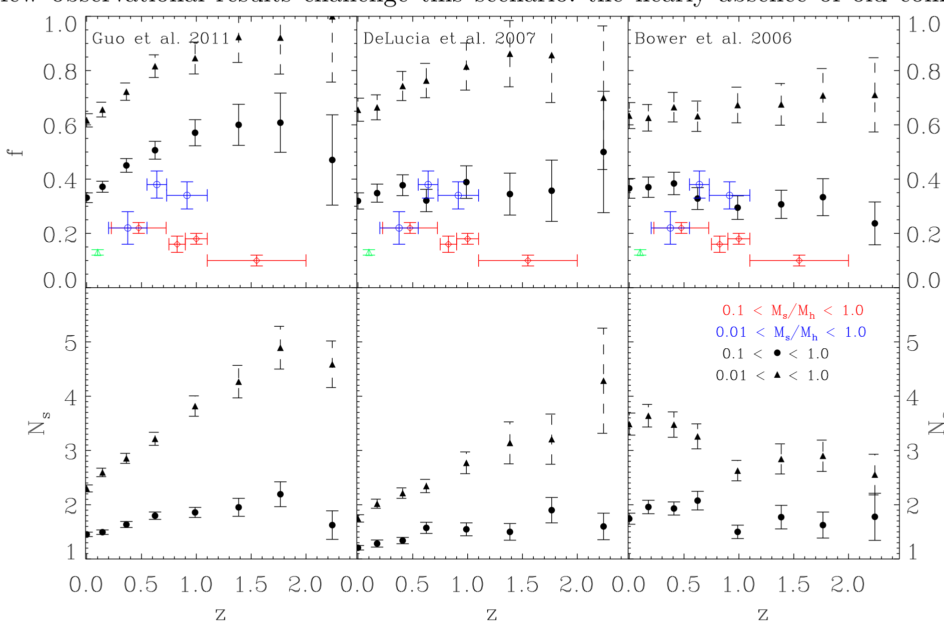


**Figure 5.** Columns stand for the results of three galaxy catalogs based on different semi-analytical models. For each model, and from top to bottom, are shown the fraction of massive galaxies that have at least one satellite within a sphere of 100 kpc radius and a projected distance smaller than 100 kpc, and the average number of satellites per massive galaxy when they have one of such objects around. The full circles (triangle) stand for the satellites with stellar mass ratios of $0.1<M_s/M_h<1$ ($0.01<M_s/M_h<1$). The error bars represent one standard deviation. The observational data from Mármol-Queraltó et al. (2012) are overplotted as red (blue) open circles (diamonds) for mass ratios of $0.1<M_s/M_h<1.0$ ($0.01<M_s/M_h<1$). The local observational reference (z=0.1) from Liu et al. (2011) for the fraction of massive galaxies with satellites with mass ratios of $0.1<M_s/M_h<1$ is plotted as a green open triangle, no data are available for smaller satellites. Figure taken from Quilis & Trujillo (2012).

massive relics in the present-day universe and the apparent few satellites that surround the massive galaxies at every redshift. Further investigations will clarify whether this discrepancy is just a matter of refining the models predictions or whether these observations will force us to change our main view of massive galaxy evolution.

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